

# Advancing Log Volume Estimation: Comparison of Modern and Traditional Approaches

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Traditional and modern approaches were compared for determining oak sawlog volume under operational conditions. Manual measurement combined with cubic formulas (Huber, Smalian, Newton, and Hossfeld), standardized volume tables (STN 48 0009:2017), computed tomography (CT) scanning, mobile applications (iFOVEA Pro, Timbeter, LogStack LiDAR, and 3D Scanner App), and a handheld mobile laser scanner were evaluated. CT scanning provided a highly detailed geometric benchmark for comparative assessment, but it should not be interpreted as a measure of true solid volume. The Hossfeld model and Newton's formula showed the closest agreement with CT-derived volumes. Among bulk-pile methods, iFOVEA Pro and LogStackLiDAR demonstrated the most balanced combination of internal consistency, speed, and operational usability. Timbeter and the 3D Scanner App showed lower detected volumes; however, these deviations cannot be interpreted as systematic without further analysis. Manual measurement remained accurate but was time-consuming and sensitive to operator variability, whereas handheld laser scanning provided high-fidelity results at the cost of increased time and expertise. Limitations of the study include a small sample size, the limited number of repeated measurements, and the absence of testing under variable environmental conditions. Future developments will likely focus on AI-based log segmentation, GIS integration, and cloud platforms enabling real-time data sharing.

DOI: 10.15376/biores.21.2.4296-4314

*Keywords:* Wood stack volume estimation; Photo-optical timber measurement; Digitalization in forestry operations; Mobile applications for log measurement; LiDAR and RGB technologies in wood logistics

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## INTRODUCTION

Accurate determination of log volume is a key commercial parameter because it directly influences pricing and other economic indicators. For this reason, precise volume measurement is essential for wood processors and traders. Many processing facilities already use photo-optical and laser-based systems integrated into stationary devices for tasks such as quality assessment, sawing-plan design, and processing.

Raw wood, the primary product of forestry, has highly variable dimensions and volume. This variability is influenced by factors such as growth conditions, tree species, harvesting methods, and site characteristics. During forest growth, wood volume is assessed at several production phases, and the accuracy of these measurements can vary significantly. Such discrepancies may lead to challenges in planning, logistics, and sales (Kunz *et al.* 2017; van Niekerk *et al.* 2020).

Another important aspect is the definition of volume—whether it includes bark, non-merchantable wood (diameter below 7 cm), or below-ground parts (Duka *et al.* 2020; Jankovský *et al.* 2023). Rules for volume calculation depend on commercial agreements and are usually specified in timber trade contracts (Ligot *et al.* 2018; Siipilehto and Rajala 2019). Traditionally, the volume of standing trees is estimated by measuring diameter at breast height (1.3 m) and total height. However, accurate height measurement in dense stands during the growing season is difficult, often resulting in deviations from actual volume. Precision forestry methods, including laser scanning, have improved these estimates, but even automated algorithms have limitations (Dalponte *et al.* 2011; Anjin *et al.* 2012; Sumnall *et al.* 2023; Wang *et al.* 2024).

In the production phase, volume determination depends on the harvesting method (whole trees, stems, assortments) and related technologies (Sedmíková *et al.* 2020; Delmaire and Labelle 2022). Multi-operation machines often include electronic systems for measuring processed logs. In motor-manual harvesting, diameters are measured manually at several points along the log, and cubic volume formulas are applied according to dendrometric rules. To adapt calculations to local conditions, national standards and volume tables are commonly used (Fonseca 2005; Tomusiak *et al.* 2016; Giedrowicz and Staniszewski 2017; Kruglov *et al.* 2017; STN 480009 2017; de Miguel-Díez *et al.* 2023). Examples include STN 48 0009 in Slovakia (2017), Guo Biao - GB/T 4814-2013 (2013) (Standards for China Market Access) and Japanese Agricultural Standard (JAS) for Log Volume Measurement (2003) (Hakoda 2010), GOST 2708-75 (1975) in Russia, and formulas, such as Doyle or Scribner, in North America. These methods assume ideal log shapes and only partially account for taper, introducing systematic errors. Moreover, manual measurement is time-consuming and prone to human error, especially when handling large volumes (Tomusiak *et al.* 2016; Giedrowicz and Staniszewski 2017).

With digital and automated measurement, some of these shortcomings can be mitigated, time can be saved, and efficiency increased. Some automated solutions are certified for accuracy verification, while others are designed for general use without authorized certification (Tomczak *et al.* 2024). Mobile applications for Android and iPhone have become increasingly popular. These employ either classical photo-optical or photogrammetric approaches, or—in the case of iPhones—integrated LiDAR sensors. In recent years, these applications have seen dynamic development, driven by rapid improvements in mobile hardware and embedded sensors. However, it is important to distinguish between measurement methods (*e.g.*, photogrammetry, structured-light scanning, LiDAR-based point-cloud acquisition) and commercial tools (*e.g.*, Timbeter, iFOVEA Pro, LogStackLiDAR), which only represent specific implementations of these methods (Ucar *et al.* 2024). This distinction has been emphasized in recent literature and is essential for proper methodological interpretation.

Given the growing adoption of automated and digital measurement methods, ensuring high accuracy in log volume determination becomes crucial—not only for operational forestry but also for subsequent processes such as timber trade, sales planning, transport logistics, and processing capacities (Moskalik *et al.* 2022). Modern research increasingly addresses non-app-based methods as well, including terrestrial laser scanning (TLS), mobile laser scanning (MLS), UAV-based photogrammetry, and deep-learning-based log segmentation, which form the scientific basis of many commercial tools.

This study aimed to compare traditional and modern approaches for determining log volume under operational conditions. In this context, “traditional approaches” refer to manual measurement of diameters and lengths combined with classical cubic volume

formulas, whereas “modern approaches” denote indirect sensing-based acquisition of log dimensions (*e.g.*, imaging, LiDAR, scanning) followed by computational reconstruction and volume estimation. Specifically, the following questions were addressed:

- (1) How do digital methods compare to traditional formulas in terms of accuracy?
- (2) Which methods offer the best balance between accuracy and operational efficiency?
- (3) What limitations and practical considerations arise when applying these methods in practice?

## EXPERIMENTAL

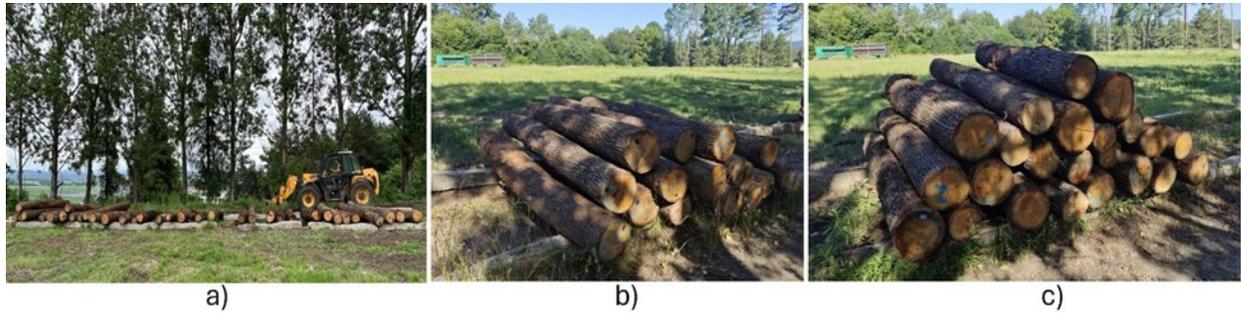
### Raw Material

For this analysis, oak sawlogs served as the primary material. Oak was chosen because of its consistently high market value (Parzych and Mandziuk 2021) and frequent occurrence in timber auctions, making it representative of common commercial practice. The material was obtained from forests in the Slovak Republic during the spring of 2025. It consisted of high-value sawlogs intended for oak blank production, regularly traded as premium assortments. Logs were sourced from multiple locations and harvested as part of standard commercial operations. Selection criteria included compliance with sawlog quality standards STN 48 0056 (2007), ensuring that the logs were free of major defects and suitable for processing into high-grade products.

In total, 38 logs were analyzed and divided into two length classes: 2.5 m (23 pieces) and 3.0 m (15 pieces). The logs originated from a private company, which declared their total volume to be 6.54 m<sup>3</sup>. However, the declared total length did not include the customary length allowance added to each log in commercial practice. According to Slovak legislation STN 48 0050 (2017), a length allowance of 1% of the nominal log length (up to a maximum of 10 cm) is added unless otherwise agreed between the supplier and buyer in a sales contract. Consequently, the actual lengths of the segments were not exactly 2.5 m and 3.0 m. Nevertheless, for volume calculation purposes, the nominal lengths (without allowance - 1%) were always used. Thus, the nominal lengths of 2.5 m and 3.0 m were consistently applied in all volume computations and method comparisons—manual formulas, mobile applications, laser scanning, and CT scanning—to ensure comparability of results. Although the actual physical lengths of the logs included the customary allowance, these were disregarded for calculation purposes, as commercial practice and Slovak standards (STN 48 0050) prescribe using nominal lengths when determining trade volumes. As a result, the comparison reflects only differences in measurement techniques, not discrepancies caused by length allowances.

Two approaches were used for determining volume, depending on the specific method applied. For manual measurement and CT scanning, each log was measured and calculated on an individual basis. In mobile laser scanning, the assortments were stacked into two piles according to their length: one pile containing the 2.5 m logs and the other containing the 3.0 m logs (Fig. 1).

The measurements were recorded at the premises of the Biotechnological Park of the LignoSilva Forest–Wood Complex Centre of Excellence, Stráž, in the cadastral area of Zvolen, Slovakia (coordinates: 48.58179049198579 N, 19.09221937368447 E).



**Fig. 1.** Arrangement of logs for volume calculation (a – individual measurement, b – 3.0 m log pile, c – 2.5 m log pile)

### Manual Measurement of Oak Logs

For volume determination using cubic volume formulas, each log was manually measured using a standard caliper and measuring tape. The parameters recorded were: exact log length and diameters over bark at the small end, large end, midpoint, and one-third of the log length from each end.

Standard cubic volume formulas were then applied according to their respective authors: Huber (Eq. 1) (Huber 1822), Smalian (Eq. 2), Newton (Eq. 3) (Smalian 1837; Bruce 1951), and Hossfeld (Eq. 4) (Hossfeld 1822). An overview of these formulas is presented in Table 1.

Manual measurement is treated here as a measurement procedure, while the cubic formulas represent analytical models used to estimate volume from measured diameters and lengths.

**Table 1.** Overview of Cubic Volume Formulas Used for Calculating the Volume of Individual Logs

Equation No. and Name	Cubic Volume Formula	Reference
1 – Huber	$V = \frac{\pi}{4} \cdot d_{1/2}^2 \cdot L$	(Huber 1822)
2 – Smalian	$V = \frac{\pi}{4} \cdot \frac{d_0^2 + d_n^2}{2} \cdot L$	(Smalian 1837)
3 – Newton	$V = \frac{\pi}{4} \cdot \frac{d_0^2 + 4d_{1/2}^2 + d_n^2}{6} \cdot L$	Newton (Bruce 1951)
4 - Hossfeld	$V = \frac{\pi}{4} \cdot \frac{3d_{1/3}^2 + d_n^2}{4} \cdot L$	(Hossfeld 1822)

In Table 1,  $L$  is the Nominal log length (centimeters),  $d_0$  is the diameter at the butt end over bark (centimeters),  $d_n$  is the top end diameter over bark (centimeters),  $d_{1/2}$  at the midpoint over bark (centimeters), and  $d_{1/3}$  at one-third of the log length over bark (centimeters).

In addition to these formulas, standardized cubic volume tables according to the Slovak national technical standard STN 48 0009 (2017) were also used. These tables provide log volume without bark, even though diameters are measured with bark. Therefore, to ensure comparability with methods that inherently include bark, the estimated

bark volume was added based on species-specific coefficients recommended in Slovak dendrometric guidelines.

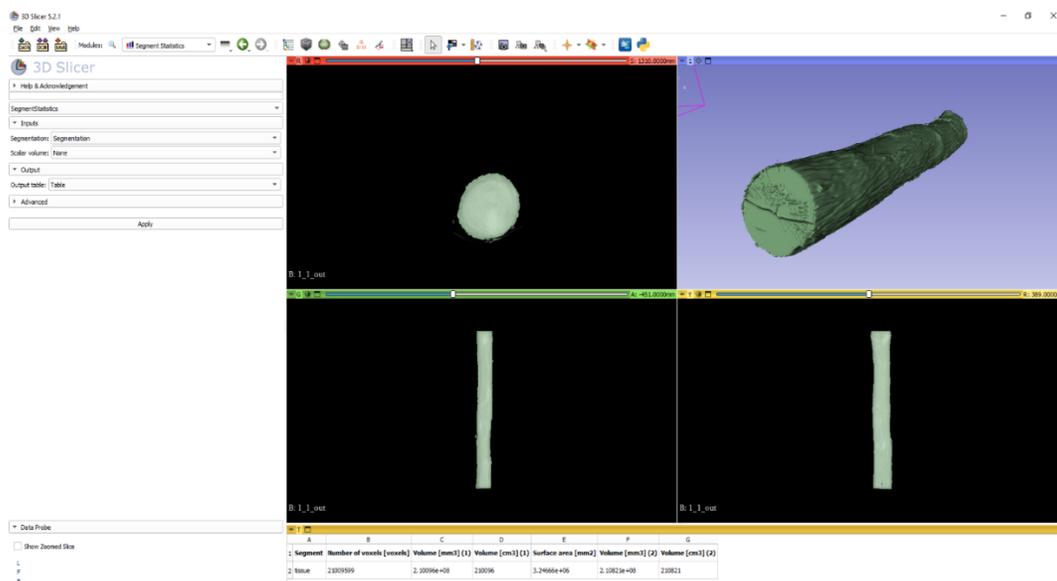
Measurements were recorded on June 3, 2025. Potential shrinkage of oak logs during the three-week interval between initial measurement and subsequent scanning was not considered, as oak exhibits minimal dimensional changes over short periods when stored in bark under outdoor conditions.

### CT Scanning of Logs and Volume Calculation

After the manual measurements, CT scanning was performed on 27 June 2025 using a Microtec CT log scanner located at the LignoSilva Centre of Excellence, National Forest Centre. The operating principle of the scanner, its parameters, and methodology have been described in detail in previous works (Gejdoš *et al.* 2023, 2025a; Vacek *et al.* 2024).

During scanning, each log was continuously fed into the rotating scanning ring *via* a rubber conveyor belt. The X-ray source was positioned opposite the detectors on both sides of the ring. Computer processing assigned a radiation absorption value to every point within the cross-sectional plane, which was then used to generate a grayscale image. The obtained data were then used to reconstruct cross-sections in the required planes. From the CT images—generated as cross-sectional slices composed of voxels measuring 1 mm × 1 mm × 10 mm—a 3D model of each log segment was constructed.

Each CT image required initial adjustment and contrast optimization in the freely available software 3D Slicer (2025). After optimization, the segmentation module was used to delineate the wood from the background, and the software automatically computed the total volume (Fig. 2).



**Fig. 2.** Segmentation and volume calculation of a 3D log model from a CT image in the 3D slicer environment

### Mobile Applications for Volume Measurement

For volume determination using mobile applications, the logs were arranged into two piles according to their lengths (Fig. 1). Most mobile tools available on the market rely on either photo-optical or LiDAR-based sensing technologies (Tomczak *et al.* 2024). These

tools have undergone considerable development and can accelerate data collection and volume calculation—sometimes by more than eightfold relative to manual methods (Tomczak *et al.* 2025).

For this study, four widely used applications were selected. Two of them were photo-optical systems: Timbeter and iFOVEA Pro. Two others were LiDAR-based: LogStackLiDAR and 3D Scanner App.

All applications were run on an iPhone 14 Pro Max. Each was used in bulk-pile mode, not single-log detection mode, to maintain comparability across tools. Although iFOVEA Pro offers individual log detection, this option was not applied here. The measurement methodologies for pile volume assessment by these applications have been described in detail in previous works (Tomczak *et al.* 2024, 2025; Gejdoš *et al.* 2025b), and these validated protocols were followed.

In this study, mobile applications are considered implementations of photo-optical or LiDAR-based sensing methods—not measurement methods themselves.

Most applications estimate gross pile volume, which includes air gaps. To convert it to net wood volume, a correction factor of 0.71 was applied (STN 48 0056). iFOVEA Pro uses similar coefficients (0.717; 0.791), confirming the common practice of correcting for void ratio. The 3D Scanner App, although not primarily designed for volume measurement, was able to compute pile shape from a LiDAR-based 3D scan; therefore, the same correction factor was used.

The volume measurements with the selected applications were performed on 2 July 2025, nearly one month after the manual measurements. Because the logs were oak sawlogs stored in bark under outdoor conditions, no significant changes in moisture content, drying cracks, or dimensional alterations occurred during this period. Each measurement within every application was performed twice, and the resulting volume represents the arithmetic mean of the two measurements, following validated protocols (Tomczak *et al.* 2024, 2025; Gejdoš *et al.* 2025b). Previous studies have shown that repeated measurements under identical conditions yield negligible variation; therefore, a single set of measurements was considered sufficient for this comparison. All applications were used on the same day and under consistent lighting conditions. The piles were placed in light shade to prevent direct sunlight exposure to the photo-optical sensors of the iPhone 14 Pro Max.

### Calculation of Volume Using a Handheld Laser Scanner

For this analysis, the handheld mobile laser scanner Stonex X200 GO was used, chosen primarily based on its availability. The Stonex X200 GO SLAM system has a collection rate of 1,900,000 points per second, a relative accuracy of 6 mm, and a range of up to 300 m. It is equipped with an RGB camera with a resolution of 5 MP and a viewing angle of  $200^\circ \times 100^\circ$ , enabling point-cloud colorization. The scanner works together with the GO app, where the scanned image is displayed in real time, allowing the scanning process to be monitored directly on a mobile phone.

The scanning trajectory was kept simple: both created piles were circled to capture complete geometry. Processing of the obtained point cloud was performed in GoPost software. The result was a dense 3D point cloud, later converted into a closed 3D object. In Cube 3D software, a selection mask was created to isolate the target pile from the surrounding environment. After isolating the pile, the terrain beneath it was interpolated to create a base for volume calculation.

The pile volume was calculated as the difference between the surface of the pile and the interpolated terrain. Because this approach, as with the 3D Scanner App, calculates

the gross pile volume including air gaps, a correction factor was applied to estimate the net wood volume. The same coefficient of 0.71, used for the 3D Scanner App, was applied in accordance with STN 48 0056 (2007).

### Evaluation of the Obtained Results

Two approaches were used to evaluate the results: (1) descriptive comparisons of the measured volumes, including absolute differences and percentage deviations between methods, and (2) statistical analysis using established tests.

To verify whether the data followed a normal distribution, two complementary tests were applied: the Shapiro–Wilk test (Monter-Pozos and Gonzáles-Estrada 2024), which is sensitive to departures from normality in small samples, and the Anderson–Darling test (Nelson 1998), which places more weight on the tails of the distribution. Homogeneity of variances was checked using Levene’s test.

Instead of treating the methods as independent groups (as in ANOVA), the analysis will treat the measurements as paired observations. A paired t-test and a calibration-type regression model will be applied in the statistical analysis section.

## RESULTS AND DISCUSSION

The results were evaluated from two perspectives: (1) determining individual log volumes using cubic formulas and CT scanning, and (2) determining bulk volume for two piles of logs grouped by length using mobile applications and a handheld laser scanner.

### Determination of the Volume of Individual Logs

The calculated volumes of all 38 oak logs obtained using cubic volume formulas, the standardized STN 48 0009 tables, and CT-based 3D reconstruction are summarized in Table 2. CT volume served as a reference benchmark for paired comparisons, not as a representation of “true volume”.

**Table 2.** Overview of the Total Calculated Volume of Oak Logs

Method	Total Calculated Volume (m <sup>3</sup> )
1 – Huber	8.689
2 – Smalian	8.857
3 – Newton	8.745
4 - Hossfeld	8.693
5 – STN 48 0009	8.411
6 - CT scanner	8.580

To verify distributional assumptions required for parametric paired comparisons, the Shapiro–Wilk and Anderson–Darling tests were applied to each method. All p-values exceeded 0.05, and the Anderson–Darling statistics were below the 5% critical value, indicating that the paired differences were approximately normally distributed. Therefore, paired parametric tests were appropriate.

Because the dataset consists of paired measurements of the same logs, ANOVA and Tukey-type post-hoc tests are not appropriate inferential tools. Inferential statistics were therefore based on paired t-tests comparing each method directly with the CT reference.

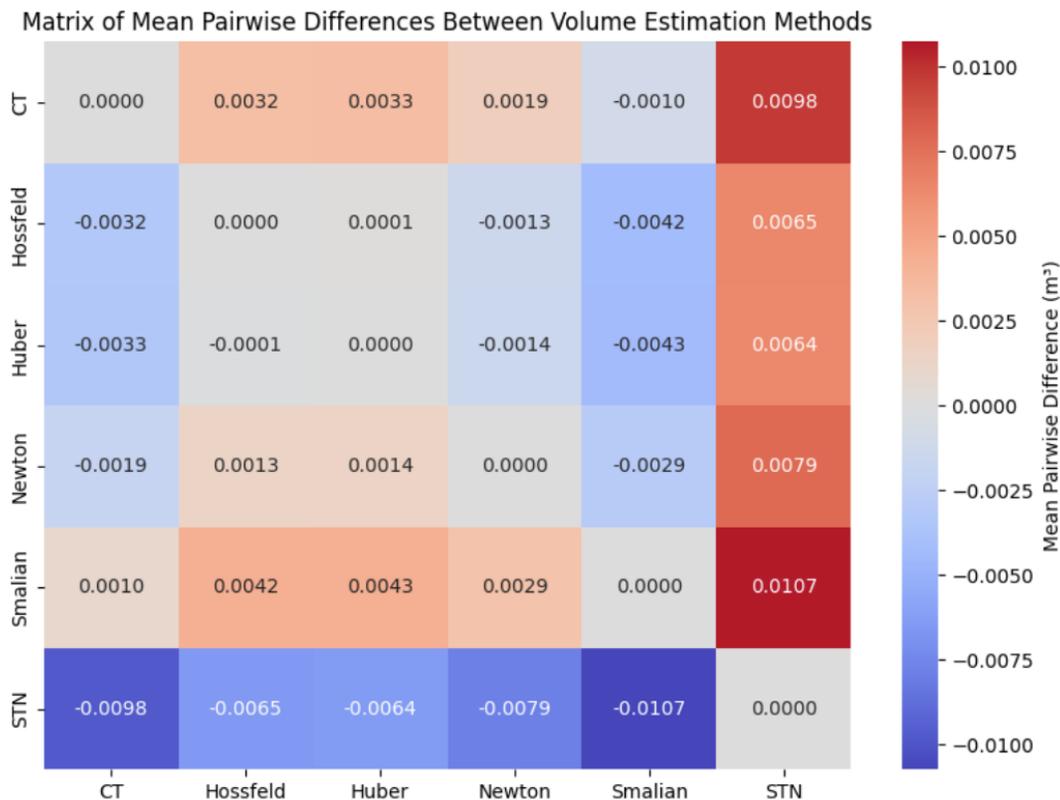
The paired t-test evaluates whether the mean difference between CT and each method is significantly different from zero (Table 3).

**Table 3.** Computed Mean Paired Differences (method-CT)

Method	Mean difference (m <sup>3</sup> )
Hossfeld	-0.003219
Huber	-0.003308
Newton	-0.001874
Smalian	+0.000994
STN 48 0009	-0.009751

Paired t-tests showed that none of the traditional cubic formulas (Huber, Smalian, Newton, Hossfeld) differed significantly from the CT-derived volume at  $\alpha = 0.05$ . In contrast, STN 48 0009 exhibited a statistically significant negative deviation, reflecting the fact that this standard expresses volume without bark while all other approaches include bark volume.

Pairwise differences between all six methods were computed as the mean of log-wise differences ( $n = 38$ ). The resulting symmetric matrix is shown in Fig. 3. These differences are descriptive and not based on ANOVA or Tukey HSD.



**Fig. 3.** Matrix of mean pairwise differences between volume estimation methods (in m<sup>3</sup>). Darker red indicates a higher positive difference between method A and method B, whereas darker blue indicates a larger negative difference. Differences represent mean log-wise deviations and do not rely on post-hoc ANOVA testing.

The descriptive differences demonstrated that no single cubic volume formula was universally superior; instead, each reflected a different geometric prototype and therefore performed differently depending on log taper, curvature, and shape regularity. In this dataset—characterized by short, relatively straight sawlogs—Newton’s mixed-curvature formulation aligned most closely with the CT-derived volumes, followed by Hossfeld and Huber.

The supplier-reported total volume (7.12 m<sup>3</sup>) underestimated all analytically derived volumes by nearly 1.5 m<sup>3</sup> compared with CT (8.58 m<sup>3</sup>). This underscores the practical importance of consistent measurement protocols and highlights potential discrepancies arising from bark conventions, rounding, and manual diameter readings.

### Determination of Oak Logs Volume by Bulk Method

Bulk volume was determined for two piles (3.0 m and 2.5 m in length) using four mobile applications and a handheld laser scanner (Table 4). For methods calculating gross pile volume, a correction factor of 0.71 was applied to estimate net wood volume. CT scanning results are included solely as a benchmark and not as an operational alternative.

The results of bulk volume determination are summarized in Table 4, with all values expressed in cubic meters (m<sup>3</sup>).

**Table 4.** Results of Bulk Volume Determination

Method	Detected Volume (m <sup>3</sup> )
LogStackLiDAR	7.663
Timbeter	7.15
iFOVEA Pro	8.50
3D Scanner App	6.10
Handheld Stonex X200 Individual trunks	7.17
Handheld Stonex X200 Trunks stacks	8.38

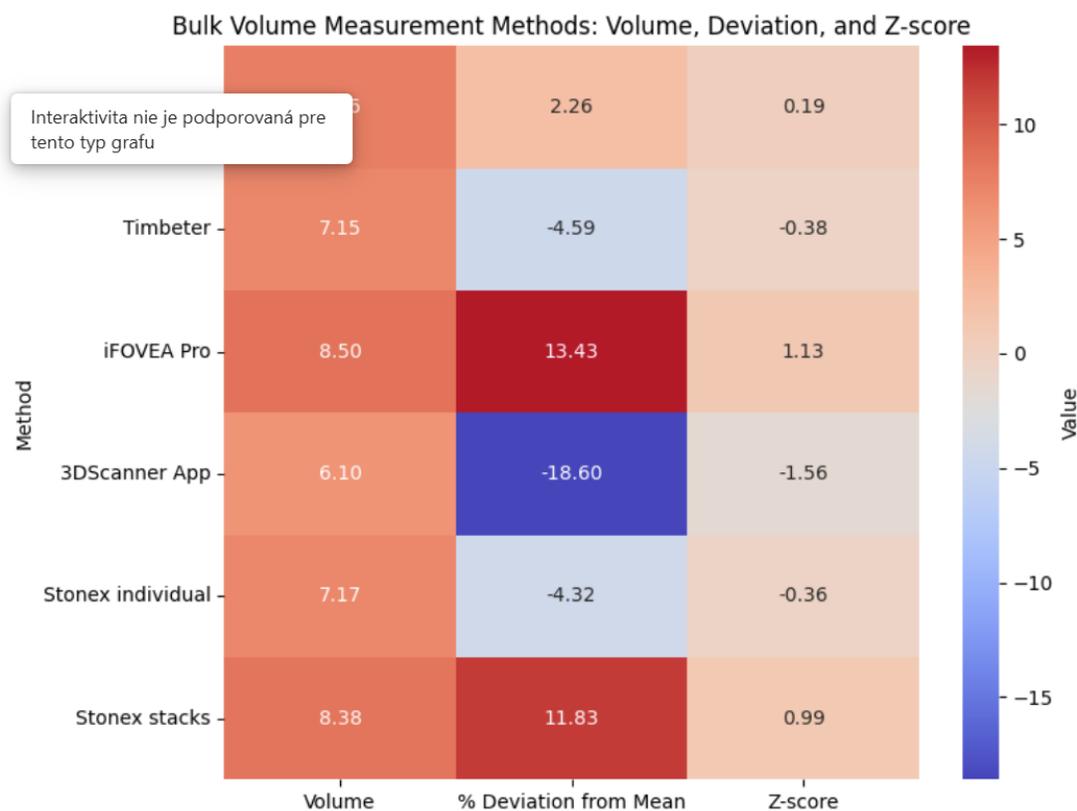
Figure 4 illustrates the filtered point cloud obtained from the handheld laser scanner (Stonex X200GO) for logs arranged in stacks. After applying the correction coefficient, the calculated volume was 8.38 m<sup>3</sup>.



**Fig. 4.** Point cloud of log stacks obtained by handheld laser scanner

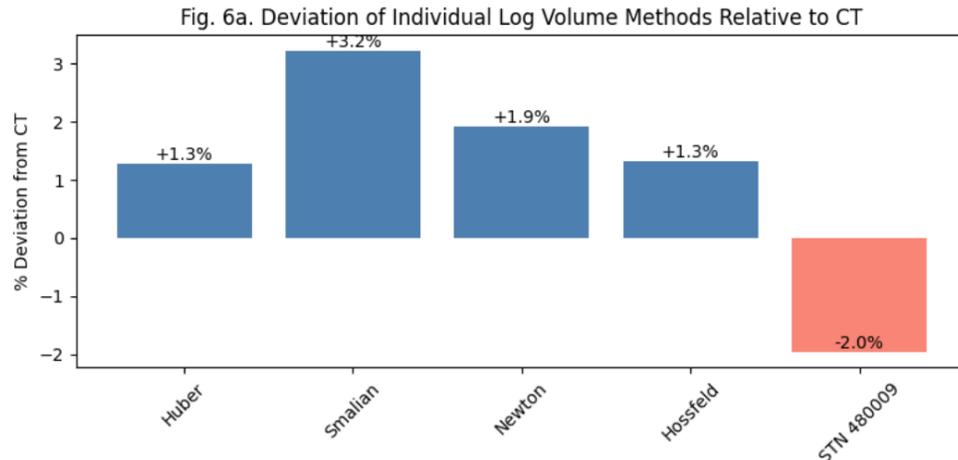
Differences among the bulk methods are shown in Fig. 5, which presents absolute volume differences ( $m^3$ ), percentage deviations from the internal mean, and Z-scores for each method. Colors indicate the magnitude of deviation. The mean of all bulk methods is used only as an internal descriptive reference and does not represent a true or external measure of accuracy. Percentage deviations and Z-scores therefore reflect internal consistency among methods and not accuracy relative to an external standard.

iFOVEA Pro and LogStackLiDAR showed the smallest deviations from the internal mean, indicating good internal consistency across their results. Timbeter and the 3D Scanner App produced substantially lower detected volumes in this dataset; however, these findings cannot be interpreted as systematic underestimation without regression-based agreement analysis. The handheld laser scanner yielded results similar to iFOVEA Pro and LogStackLiDAR, indicating its applicability for operational contexts requiring higher geometric fidelity.

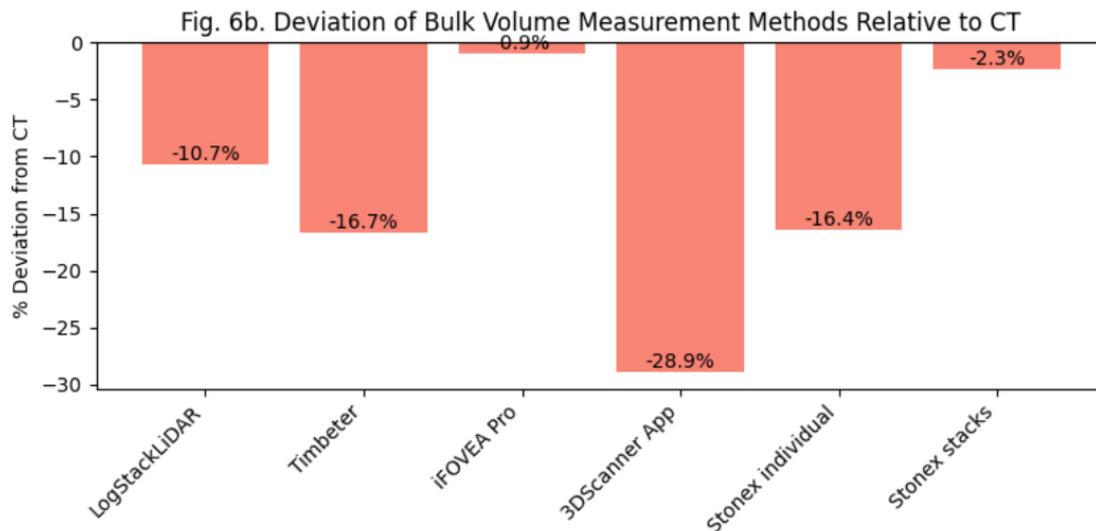


**Fig. 5.** Heatmap comparing bulk volume measurement methods based on detected volume ( $m^3$ ), percentage deviation from the internal mean, and Z-scores

Figure 6 illustrates the percentage deviations of individual and bulk-pile methods from the CT-derived benchmark. These deviations represent descriptive comparisons only, as CT was used solely as an internal reference and not as an indicator of “true solid volume.”



**Fig. 6a.** Percentage deviation of individual log-based volume estimation methods relative to the CT benchmark



**Fig. 6b.** Percentage deviation of bulk-pile volume measurement methods relative to the CT benchmark

To complement the deviation-based evaluation, operational characteristics of the bulk methods were compared using four normalized criteria.

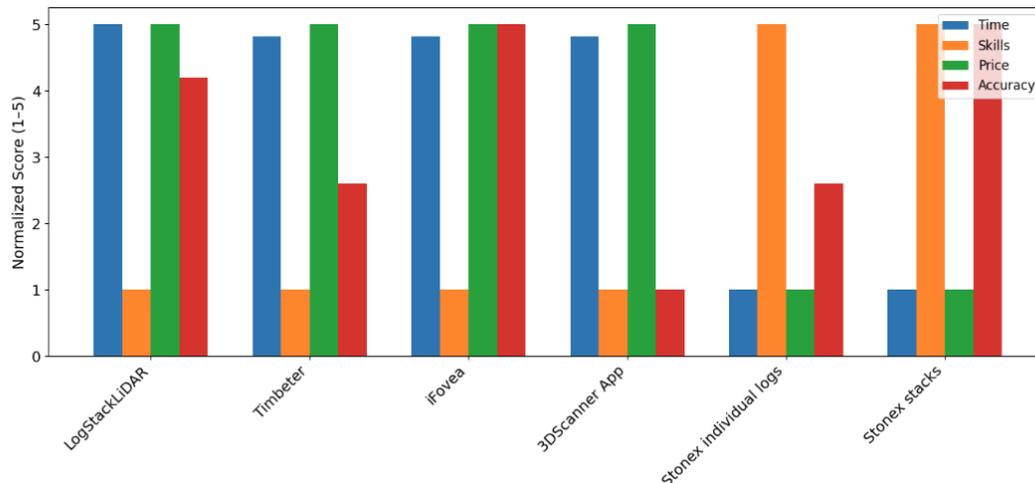
To evaluate the overall suitability of the methods, four parameters were considered:

1. Time – measured as the duration from setup to obtaining the final volume result;
2. Cost – based on the market price of required equipment and software;
3. Accuracy – expressed as deviation from the mean of all bulk methods;
4. Required skills – assessed qualitatively based on the complexity of operation and data processing steps.

Higher normalized scores across all four criteria indicate more balanced operational performance.

Figure 7 presents a grouped bar chart comparing these criteria on a normalized scale from 1 (least favorable) to 5 (most favorable). Only bulk-pile methods were included, and

normalization was performed across this subset. LogStackLiDAR and iFOVEA Pro achieved the most balanced performance, combining relatively fast operation, moderate equipment cost, and good internal consistency. Timbeter scored well for time and cost but showed larger deviations in detected volume. The 3D Scanner App performed well in terms of speed and affordability but poorly in volume estimation. Stonex-based methods demonstrated relatively high geometric precision but required substantially more time and operator expertise.



**Fig. 7.** Grouped bar chart comparing bulk volume measurement methods based on four normalized criteria: time (1 = slow, 5 = fast), required skills (1 = high, 5 = low), price of equipment (1 = expensive, 5 = cheap), and relative internal accuracy (1–5).

From these results, it can be cautiously concluded that photo-optical and LiDAR-based mobile applications can largely replace manual measurement methods in operational conditions. However, their performance depends strongly on pile geometry, stacking regularity, environmental conditions, and the applied correction factors. The handheld laser scanner offers an alternative for higher precision but at the cost of increased time and operator effort. CT scanning remains the most geometrically detailed benchmark available in this study, but it should not be interpreted as the “true” solid volume and is unsuitable for routine operational use due to its cost and specialized purpose.

## Discussion

Digitalization and the implementation of precision forestry methods have become key components of modern operational practice, supporting both techno-economic optimization and forest resource assessment. These technologies have advanced rapidly over the past decade (Atkins *et al.* 2020; Buchelt *et al.* 2024). Until recently, quantitative measurements and volume determination relied largely on manual procedures, which were time-consuming and dependent on the experience and consistency of personnel. This was particularly relevant in commercial contexts, where volume measurement forms the basis for invoicing in the timber trade. Gradual digitalization and automation, supported by multi-operator machines and improved sensing technologies, have significantly reduced this reliance (Vähä-Konka *et al.* 2024).

With the rapid development of mobile devices, application-based tools for field measurements have become increasingly common. These tools are frequently used for lower-quality assortments intended for industrial processing, typically characterized by

smaller diameters and large traded volumes (Tomczak *et al.* 2025). Their primary goals include reducing labor time, improving data consistency, and simplifying field measurements.

When selecting a method for volume calculation, stakeholders must consider accuracy, repeatability, and operational limitations. A common approach to assess accuracy is comparing results with manual measurements, as applied in this study. Previous studies reported deviations for iFOVEA Pro ranging from  $-5.2\%$  to  $+0.5\%$  (Berendt *et al.* 2024),  $+5.1\%$  to  $+8.0\%$  (Tomczak *et al.* 2024), and  $0.46\%$  to  $1.97\%$  (Cremer and Blasko 2018). Tomczak *et al.* (2025) found an average difference of  $+4.2\%$ . In the present study, the deviations observed for iFOVEA Pro relative to manual formulas and STN 48 0009 ranged from  $-4.03\%$  to  $+1.06\%$ , which is within the range reported in previous literature and demonstrates reasonable internal consistency across methods.

For Timbeter, Karhä *et al.* (2019) reported accuracy up to  $+9\%$ , while Ucar *et al.* (2024) found it more accurate than iFOVEA Pro under Turkish conditions. In contrast, the present results showed that Timbeter produced lower detected volumes in this specific dataset. While the magnitude of these deviations was substantial, they cannot be judged to be systematic underestimates without analysis based on regression. LogStackLiDAR also produced lower detected volumes in this study, whereas previous work by Tomczak *et al.* (2024, 2025) reported deviations between  $+2.7\%$  and  $+3.5\%$ . One plausible explanation lies in the relatively small pile size and irregular arrangement used in this study, which increases the proportion of air gaps and thus magnifies the influence of the correction factor applied to gross pile volume.

To date, no published comparisons exist between CT-based 3D models and mobile applications. Gergel' *et al.* (2022) found that CT-derived volumes were closest to STN 48 0009 (2017) tables, followed by iFOVEA Pro and the Hossfeld formula. The present results similarly confirm that CT scanning provides a detailed geometric benchmark; however, CT should not be interpreted as a measure of true solid volume, but rather as a high-resolution comparative reference.

Accuracy differences generally depend on assortment quality, pile arrangement, and user skills (Cremer and Blasko 2018). Applications requiring manual input—such as iFOVEA Pro—are more sensitive to operator experience, particularly when defining reference widths or pile boundaries. In contrast, LogStackLiDAR relies on automated point-cloud capture and thus reduces user-dependent variation. Further research should evaluate how lighting, weather, and environmental conditions influence photo-optical measurements, as such effects were beyond the scope of this study.

Digitalization offers advantages in efficiency and the ability to create verification databases (Jodłowski *et al.* 2016; Moskalik *et al.* 2022; Berendt *et al.* 2024). However, time demands differ markedly. LogStackLiDAR was more than twice as fast as iFOVEA Pro and 2.7 times faster than manual measurement (Tomczak *et al.* 2025), and similar trends were observed in the present dataset. Manual measurement was the most time-consuming, while CT image processing and point cloud evaluation required the greatest post-processing time. It is important to distinguish handheld mobile scanning from terrestrial laser scanning (TLS), which typically refers to static scanning; the two technologies differ significantly in accuracy, data completeness, and application context.

The accuracy and repeatability of manual measurements depend strongly on operator skill and the precision of diameter and length measurements. Digital applications, in contrast, reduce operator influence but may introduce uncertainties related to image quality or sensor limitations. Studies by Tomczak *et al.* (2025) and Purfürst *et al.* (2023)

noted that LiDAR-based approaches still have potential for improvement, particularly in estimating gross pile volumes and accounting for air gaps. The current results support these findings, demonstrating that corrected point-cloud-based volumes better approximate reference values than uncorrected gross pile volumes.

Overall, this study demonstrated that mobile applications based on photo-optical and LiDAR technologies offer an efficient supplement to traditional manual methods for roundwood volume determination. In terms of relative accuracy, the smallest deviations in this study were observed for the Hossfeld formula and iFOVEA Pro when compared to the CT benchmark; however, such deviations should be interpreted cautiously, as CT represents only a geometric reference and not a true solid-volume standard. Likewise, applications such as the 3D Scanner App and Timbeter exhibited negative deviations in this dataset, but such findings do not constitute evidence of systematic bias without further statistical modeling.

In terms of time, cost, and required skills, iFOVEA Pro and LogStackLiDAR provided the most balanced performance. Traditional methods remain accurate but are labor-intensive and require skilled personnel. CT scanning offers exceptional geometric detail but is only economically feasible where the technology is already available. Based on the results, the following recommendations for operational practice can be proposed:

1. Method selection:

Choose methods with verified performance under given conditions. For invoicing and commercial use, validated solutions such as iFOVEA Pro, LogStackLiDAR, CT-based references (where available), or traditional formulas (e.g., Hossfeld) may be appropriate.

2. Assortments and stack arrangement:

Accuracy decreases with irregular stacks and higher-quality assortments; in such cases, higher-precision methods should be preferred.

3. Training:

Digital tools require proper training in data capture and evaluation. The quality of outputs depends on adherence to recommended procedures.

4. CT scanning as a supplementary method:

Where accessible, CT can support high-precision evaluation and verification without additional measurement costs.

5. Economic efficiency:

Technology selection should consider not only accuracy but also equipment costs, software requirements, and time efficiency.

Future developments may include machine-learning-based log segmentation, automated shape recognition, and improved volume estimation from images or point clouds. The increasing shift to cloud-based environments will enhance real-time data sharing and integration with GIS platforms, supporting planning and logistics. Virtual 3D models of storage yards and forest stands will enable simulation of harvesting, logistics, and processing.

In conclusion, selecting an appropriate method for determining log volume depends on operational conditions, accuracy requirements, and available resources. Continued development of digital tools is likely to further improve efficiency and transparency in wood trade and forestry logistics.

### *Limitations of the study*

- The sample size was small, consisting of only two log piles.
- Only one repeated measurement was performed for each pile, which may affect robustness.
- The study did not include tests under varying lighting or weather conditions, which could influence photo-optical measurements.
- The use of a standardized correction factor to adjust gross pile volumes may introduce additional sources of error.

## **CONCLUSIONS**

1. Computed tomography (CT) scanning provided the most geometrically detailed benchmark in this study, allowing consistent comparative assessment of traditional and digital methods to estimate the volume of logs in an orderly pile. CT should, however, be interpreted only as a high-resolution reference rather than a measure of “true” solid wood volume.
2. Among traditional formulas, the Hossfeld formula exhibited the smallest deviation relative to CT-derived volumes, confirming its suitability for operational contexts requiring consistent individual-log volume estimation.
3. Photo-optical and LiDAR-based mobile applications demonstrated strong potential to support bulk volume estimation under operational conditions. In this study, iFOVEA Pro and LogStackLiDAR showed the most balanced combination of internal consistency, speed, and operational usability.
4. Applications such as Timbeter and the 3D Scanner App showed negative deviations in this dataset; however, these deviations cannot be interpreted as systematic without further regression-based agreement analysis. Their use in commercial settings may therefore require calibration or verification procedures.
5. Manual measurement remains accurate but is labor-intensive and prone to operator-dependent variability. Its suitability is highest in situations where digital tools are not available or where regulatory frameworks require manual measurements.
6. Handheld mobile laser scanning provided results comparable to the more accurate mobile applications, but they required more time and operator expertise. It represents a viable option where higher geometric detail is prioritized over speed.

## **ACKNOWLEDGMENTS**

This work was supported by the Slovak Research and Development Agency [grant numbers APVV-22-0001; APVV-21-0032; APVV-20-0118]; Ministry of Education, Research, Development and Youth of the Slovak Republic [grant number VEGA 1/0604/24]; Horizon Europe – Teaming for Excellence [Grant Agreement #101059552] and within the framework of the Recovery and Resilience Plan of the Slovak Republic project numbers 09I05-03-V02-00001; 09I03-03-V04-00341.

The authors thank Mr. Jens Fuglsang Røge and the company Dalgas for providing a free license for the LogStackLidar Pro application for use and evaluation within this research.

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Article submitted: December 8, 2025; Peer review completed: January 18, 2026; Revised version received: March 13, 2026; Accepted: March 20, 2026; Published: March 30, 2026.

DOI: 10.15376/biores.21.2.4296-4314